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THE EVOLUTION OF CANDU® FUEL CYCLES AND THEIR POTENTIAL CONTRIBUTION TO WORLD PEACE

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Abstract

The CANDU® reactor is the most versatile commercial power reactor in the world. It has the potential to extend resource utilization significantly, to allow countries with developing industrial infrastructures access to clean and abundant energy, and to destroy long-lived nuclear waste or surplus weapons plutonium. These benefits are available by choosing from an array of possible fuel cycles. Several factors, including Canada's early focus on heavy-water technology, limited heavy-industry infrastructure at the time, and a desire for both technological autonomy and energy self-sufficiency, contributed to the creation of the first CANDU reactor in 1962. With the maturation of the CANDU industry, the unique design features of the now-familiar product – on-power refuelling, high neutron economy, and simple fuel design – make possible the realization of its potential fuel-cycle versatility. Several fuel-cycle options currently under development are described.

Introduction

CANDU® (Canada Deuterium Uranium) is the technology at the heart of Canada's domestic and export nuclear power industry. CANDU reactors are heavy-water cooled and moderated, and utilize natural-uranium UO_2 fuel. The fuel is in the form of half-metre-long cylindrical bundles, typically containing 37 clustered elements. Twelve bundles sit end-to-end within a pressure tube, roughly six metres long, through which pressurized heavy-water coolant is circulated. Several hundred pressure tubes form the fissile core, within a horizontal tank (the "calandria") of low-pressure heavy-water moderator. CANDU reactors are continuously refuelled at full power, using remotely-operated machines that connect to individual fuel channels (Whitlock, 2000).

There are currently 23 CANDU reactors in operation and six under construction around the world, for a global market share of 6%. International CANDU owners include South Korea, Argentina, Romania, India, and Pakistan. The six units under construction are located in China (two) and Romania (four).

Two models of the CANDU reactor are currently marketed by Atomic Energy of Canada Limited (AECL). CANDU 6 has a capacity of approximately 700 MWe, and is the model operated or under construction by all international CANDU owners. The CANDU 6 design is a proven product that has been in commercial operation for almost 20 years.

CANDU 9, with a capacity of approximately 900 MWe, is similar in many ways to CANDU-6, but has been developed for a larger electricity market. CANDU 9 is based upon the model used at Canada's newer multi-unit stations, converted to stand-alone form.

The Origin of CANDU

The CANDU reactor concept evolved from natural-uranium, heavy-water research reactor technology developed in Canada in the 1940s and 1950s. The first reactor outside the United States, ZEEP, was started up at Chalk River Laboratories (now the major research site for AECL) in 1945 September. This was followed by the larger NRX reactor in 1947, and the NRU reactor in 1957.

In the 1950s, Canada turned to the development of civilian electricity production with nuclear power. Having large reserves of uranium ore, an established infrastructure for heavy-water technology, and no large-scale uranium-enrichment or fuel-reprocessing capability, Canada focused its efforts on a natural-uranium power reactor design, moderated by heavy water, with an open-ended fuel cycle (no reprocessing).

Further details of the CANDU concept were shaped by socio-economic factors: Canada favoured a technology that could be developed as much as possible within its own borders, and, more importantly, Canada lacked the heavy industrial infrastructure needed to manufacture large pressure vessels. Thus the essential characteristics of CANDU technology came together: pressure-tube geometry, simple fuel design, natural-uranium once-through fuel cycle, and on-line refuelling.

These features were present in Canada's prototype CANDU power plant, NPD (25 MWe), which started up in 1962. The features were scaled up for a larger prototype, Douglas Point (210 MWe), in 1966, and again for the first large-scale CANDU power plant, Pickering-1 (540 MWe), in 1971. All subsequent CANDU plants have built on this foundation in an evolutionary manner, incorporating technological advances around a fundamental design concept and philosophy.

CANDU Fuel-Cycle Flexibility

To be commercially viable with a natural-uranium fuel cycle, there is an absolute need for high neutron economy. From the outset, this led to design and operating decisions that give the CANDU design the most efficient neutron utilization of any power reactor in the world. It bestows a high degree of fuel-cycle flexibility that makes CANDU reactors attractive in a variety of current and evolving markets (Boczar, 1998).

A large moderator-to-fuel ratio in the CANDU lattice creates a well-thermalized spectrum that is essentially independent of fuel type.

On-power refuelling and small (half-metre-long) fuel bundles allow almost unlimited capability to shape the axial power distribution, if necessary. Variation of reactivity along a fuel channel can be largely controlled by the fuel shuffling strategy. This allows a variety of enrichments and fissile loadings to be utilized in existing CANDU designs, including slightly-enriched uranium (SEU), mixed oxides (MOX) of plutonium, uranium or thorium, and inert-matrix fuels (containing no fertile material).

The ability to operate with low-fissile-content fuel suggests a unique synergism between light-water reactors (LWR) and CANDU reactors, since the U-235 fraction in spent LWR fuel exceeds that of natural uranium. Direct-transfer strategies between LWR and CANDU have additional anti-proliferation advantages.

High neutron economy allows CANDU reactors to extract up to twice as much thermal energy from fissile material compared to LWR reactors, depending on the nature of the fissile material.

High neutron economy leads to a high conversion ratio, which can approach unity if self-sufficient thorium fuel cycles are utilized.

Bidirectional fuelling (adjacent channels fuelled in opposite directions) provides a natural flattening of the axial flux, and a high degree of axial symmetry.

Control of fuel management on a channel-by-channel basis helps to shape the radial flux across the core. The potential high burnup of enriched fuel cycles can be traded off for increased power in the outer zone of the core, flattening the radial flux. This permits more power to be extracted from the core, while keeping within the same rating limits.

Being able to selectively fuel channels across the core allows the phased introduction of new fuel, during a transition from one fuel type to another.

Adjuster rods, normally used to flatten the flux in the natural-uranium-fuelled core, can be replaced or eliminated with the use of enriched fuel, allowing further flexibility in accommodating advanced fuels.

Most CANDU reactors have failed-fuel detection systems, and on-power refuelling enables the prompt removal of failed fuel. This reduces the risks in terms of safety and cost associated with the introduction of new fuel. In addition, the CANDU core includes an extensive array of in-core flux detectors, ensuring that the power distribution is well characterized, regardless of the fuel type or fuel-management scheme.

Finally, the CANDU bundle design itself is flexible, in that different fuel types can be incorporated into different rings of pins. The most exotic arrangements can be modelled with confidence because the CANDU lattice ensures a strong consistency in the neutron spectrum.

Natural Uranium

The natural-uranium fuel cycle remains an attractive option for current and prospective CANDU owners, for a variety of reasons.

The fuel itself is simple, consisting of only seven basic components, and can be easily manufactured in many countries.

The use of natural uranium avoids a requirement for uranium-enrichment capability, and decouples owners from the narrowly controlled uranium- enrichment market. It also avoids the creation of depleted-uranium enrichment-plant tails, meaning less "front-end" environmental impact.

Uranium requirements are about 30% lower than for LWR enriched-uranium fuel cycles, leading to lower fuelling costs and additional "front-end" environmental benefits.

The "back-end" costs are comparable between CANDU reactors and LWRs, despite a higher volume of spent-fuel production with CANDU (OECD/NEA, 1993). Long-term disposal costs are primarily determined by heat load in a repository, and the lower burnup of CANDU fuel translates to significantly lower heat load. Additional cost savings arise from the small size and simplicity of the CANDU fuel bundle, which reduces the complexity of the emplacement system (Allan, 1997).

Slightly-Enriched Uranium

Additional benefits are achieved by utilizing SEU fuel cycles in CANDU reactors. With enrichments between 0.9% and 1.2%, fuel-cycle costs are reduced by 20% to 30% relative to the natural-uranium fuel cycle, largely due to similar reductions in uranium requirements. Spent-fuel costs are reduced by up to 30%, due to higher burnups achieved with SEU (Baumgartner, 1998).

Higher fuel burnup can be traded off against higher core power using SEU. Differential refuelling rates can be used to raise the power in the outer channels of the core, flattening the radial flux distribution. This allows plant uprating without exceeding existing limits on maximum bundle or channel power.

In new CANDU plants, this strategy of flux flattening can be used to increase the nominal power output without increasing the core size. The CANDU-9 design, normally rated at 935 MWe, can be increased to about 1100 MWe, an 18% increase.

SEU can be used to tailor the reactivity coefficients of the CANDU lattice. In particular, the void-reactivity coefficient can be tailored to meet any customer's requirements, using a combination of SEU and a strong neutron absorber in different locations within the fuel bundle.

Self-Generated Fissile Material

An option exists with all thermal nuclear power technologies to reprocess the spent fuel and recycle depleted uranium or self-generated plutonium back into the fuel cycle. The decision to pursue these options is based upon economic and resource-availability arguments.

In CANDU reactors, the spent fuel contains depleted uranium on par with the tails from enrichment plants (~0.2%). Therefore, there is no incentive to recycle uranium from spent CANDU fuel. Self-generated plutonium is also dilute in spent CANDU fuel, typically 2.6 g fissile Pu/initial kg U. The plutonium in LWR spent fuel is roughly twice that concentration.

Since reprocessing costs are dependent upon fissile concentration and the amount of material that has to be handled, there is little incentive to reprocess CANDU fuel, especially in comparison with LWR fuel.

CANDU/LWR Synergism

Although little incentive exists for the extraction of fissile material from spent CANDU fuel, based upon its low fissile concentration, the opposite is true for spent LWR fuel. Depending upon initial enrichment and burnup, spent LWR fuel contains about 0.9 wt% U-235 and 0.6% fissile plutonium.

Since the U-235 content exceeds that of natural uranium, CANDU technology offers the unique option of uranium recycling without reenrichment. This "recovered uranium" (RU) fuel cycle would have all the benefits of SEU fuel cycles described above, and would extract at least 25% more energy from the mined uranium going into the LWR fuel cycle. Compared to reenriching the RU for use in an LWR, about twice as much energy can be extracted by burning it without reenrichment in a CANDU reactor.

Twice the energy can also be extracted from burning LWR-recycled plutonium in a CANDU reactor, compared to using an LWR. In general, therefore, CANDU technology is an efficient vehicle for the recovery of fissile material at the back end of the LWR fuel cycle.

The remaining material after fissile-material recovery would be the actinide and fission-product waste. Responding to international interest in the destruction of actinide waste in reactors, CANDU fuel cycles that burn this material have been studied (Chan, 1997; Verrall, 1998). An "inert-matrix" carrier using SiC has high thermal conductivity, leading to low fuel temperatures and other safety benefits. The absence of uranium precludes the creation of additional plutonium and higher actinides, and leads to high net destruction rates. Studies using the unadjusted mix of plutonium and actinides from spent LWR fuel show a net destruction efficiency of 60% for the total actinide inventory, and 90% for the fissile inventory.

In addition to its high neutron economy, the CANDU reactor's on-power refuelling capability is key to the success of this process. With no uranium in the initial fuel mix, reactivity drops rapidly and must be matched by an increased fuelling rate. The refuelling strategy can be optimized by shuffling bundles within and between channels.

CANDU technology offers another unique option for the back end of the LWR fuel cycle, which completely avoids the need for wet reprocessing and fissile-material recovery. The "DUPIC" fuel cycle, or "direct use of spent PWR fuel in CANDU", utilizes the non-separated, non-enhanced waste product of LWRs directly as CANDU fuel (Keil, 1992).

The transfer from LWR to CANDU can be literally "direct", involving only the cutting of spent LWR fuel rods to CANDU length (~50 cm), resealing (or double-sheathing), and reengineering into cylindrical bundles suitable for CANDU geometry.

Alternatively, a dry reprocessing technology has been developed which removes only the volatile fission products from the spent LWR fuel mix (Lee, 1998; Sullivan, 1998). After removal of the cladding, a thermal-mechanical process is used to reduce the spent LWR fuel pellet to a powder, which is then sintered and pressed into CANDU-sized pellets.

The DUPIC process is much simpler than conventional wet-chemistry techniques for reprocessing, and promises to be cheaper. It presents a significant anti-proliferation benefit as well, since radioactive fission products and fissile material are not separated. In addition, since the heat load of spent DUPIC fuel is similar to that of the original spent LWR fuel, disposal requirements do not increase. However, since approximately 50% more energy can be derived from LWR fuel by burning it as DUPIC fuel in a CANDU reactor, the disposal cost is expected to be lower than either spent LWR or CANDU fuel (Baumgartner, 1998).

Between the extremes of conventional reprocessing and the DUPIC fuel cycle, a spectrum of options exists. The CANDU reactor’s high neutron economy offers many options for exploiting the CANDU/LWR synergism, allowing customization to meet local requirements and capabilities. Pursuing these various options requires international cooperation, such as the Canada-South Korea partnership that has pioneered the DUPIC process. South Korea has a fleet of both LWR and CANDU reactors, and can thus benefit from the synergism within its existing nuclear infrastructure (Lee, 1998).

Disposition of Ex-Weapons Plutonium

CANDU reactors have been proposed as a vehicle for the disposition of weapons-grade plutonium declared surplus due to global disarmament treaties (US NAS, 1994). The high neutron economy of the CANDU reactor offers a technically efficient route for this disposition, while Canada’s neutral, third-party role offers a symmetric, simultaneous approach that has political advantages.

As part of a tripartite agreement between Canada, the United States, and Russia, AECL is currently investigating a fuel-bundle design that incorporates depleted uranium in the inner fuel pins, and weapons-grade plutonium mixed with uranium in the outer fuel pins. The plutonium concentration varies between 1% and 5%. Using two CANDU reactors located in Ontario, Canada, the studies predict that 50 tonnes of ex-weapons plutonium can be processed in 15 to 25 years, depending on the fuel design (Cox, 1998).

The disposition of ex-weapons plutonium in CANDU reactors (or any reactor type) has three aspects: it is emplaced in a highly radioactive matrix, its total inventory is reduced, and its isotopic mixture is denatured from weapons- to reactor-grade.

Ex-weapons plutonium dispositioning represents a variation on fuel-cycle themes already discussed, and displays the adaptability of CANDU technology to specific needs.

Thorium Fuel Cycles

There has long been an attraction for fuel cycles using thorium as a thermal breeder of fissile material (U-233). Thorium is three times as abundant as uranium in the earth’s crust, and U-233 is valuable as a fissile material due to its high value of fission neutrons produced per thermal neutron absorbed (eta).

Existing CANDU reactors can operate on thorium fuel cycles, with comparable fuel-cycle costs to the natural-uranium cycle and with improved uranium utilization. While ultimate efficiency is achieved with a self-sufficient cycle that relies only on bred U-233, economical once-through thorium (OTT) cycles can greatly extend uranium resources.

Several options have been identified for the use of OTT in CANDU reactors (Milgram, 1984), and on-power refuelling is the key to successful exploitation of this material. Two general approaches have emerged: the "mixed-core" approach, and the "mixed-fuel-bundle" approach (Boczar, 1998).

In the "mixed-core" approach, a number of "driver" channels provide the flux requirements for a fewer number of "breeding" channels filled with thorium-oxide fuel. This is the conventional CANDU-OTT strategy, and has the potential to be competitive, in terms of resource utilization and economics, with both natural-uranium and SEU fuel cycles (Milgram, 1982; Dastur, 1995). Complex fuel management is required to handle the different characteristics and residence times of the two fuel types.

In the "mixed-fuel-bundle" approach, thorium oxide is contained in the central elements of a fuel bundle, and SEU is contained in the outer elements. Although uranium utilization and thorium irradiation are not as good as in the "mixed-core" approach, uranium utilization is improved over the natural-uranium cycle (but not SEU), with comparable costs. Fuel management is much simpler than in the "mixed-core" approach, and refuelling rates are about a third of that required with natural uranium (Chan, 1998).

An extension of the CANDU-OTT cycle is the "direct self-recycle" of the thorium elements bearing U-233, into new "mixed-bundles" containing fresh SEU elements. This is an excellent example of a proliferation-resistant fuel-recycle option (Boczar, 1999).

In the long term, the CANDU reactor is synergistic with fast-breeder reactors (FBRs), where a few expensive FBRs could supply the fissile requirement of cheaper, high-conversion-ratio CANDU reactors, operating on the thorium cycle.

Thorium fuel cycles have additional benefits beyond uranium resource extension. Both the thermal conductivity and melting point of thorium oxide are higher than that of uranium oxide (by 50% and 340ºC, respectively). Thorium oxide is chemically very stable, does not oxidize, and creates fewer minor actinides than uranium. Even with the existence of economical uranium fuel cycles, thorium can be used to simultaneously extend resources and create a "mine" of safeguarded U-233 for future exploitation.

Contribution to World Peace

Abundant energy drives economic development, which can raise a country’s standard of living and ultimately improve the prospects for peace in a region. This essential truth fuels a global escalation in energy demand that defies even highly optimistic energy-conservation projections (Nathwani, 1992; Rossin, 1991). The world is only at the dawn of a global equalization of wealth, underlined by the fact that eighty percent of the global population lives in developing countries, and one-third currently lacks access to electricity (Rhodes, 2000).

Global energy consumption is expected to see a 60% increase by the year 2020, and up to a 400% increase over the 21st century. Two-thirds of this increase will occur in developing countries (Rhodes, 2000; Rossin, 1991; US EIA, 2000).

For the extended benefits of abundant energy supply to be realized, however, new supply technology must be sustainable for the host country, in economic and environmental terms (Rhodes, 2000).

CANDU technology can uniquely offer abundant, clean energy supplies to developing countries. Its fuel-cycle flexibility decouples owner countries from the uranium-enrichment market, and allows tailoring to match local resources (economic and natural).

The simple design of the fuel and core is within the means of many industrial infrastructures, which was an attraction for Canada itself at the outset of its nuclear power development. A large technology-transfer component is thus typical with the sale of a CANDU reactor. This is not only conducive to local industry participation in construction and maintenance, but it also catalyzes industrial and technological development as a whole for the host country.

Political stability is enhanced by long-term fuel-supply assurances, and CANDU's fuel-cycle flexibility introduces an array of options for extending uranium resources with existing technology. Fuel supplies can be extended without the necessity of separating plutonium, or alternatively, better use can be made of separated plutonium and the transuranic waste that accompanies it.

Advanced fuel cycles with low proliferation risks are possible in existing CANDU reactors, such as the direct use of spent LWR fuel without reprocessing, the use of RU from spent LWR fuel without reenrichment, the use of unseparated plutonium/actinide mixtures, and the use of U-233 in once-through cycles.

CANDU's fuel-cycle flexibility also makes it the most efficient technology for the drawing-down of ex-weapons plutonium stocks. This is an important contribution in the drive to rid the world of nuclear weapons, once international treaties have removed them from active deployment.

Summary

In developing a reactor that economically extracts energy from natural uranium, Canada has created a versatile machine that can be tailored to suit any market. High neutron economy, simple design, and on-power refuelling open the door to a variety of fuel types and enrichments with compelling economic incentives.

While the natural-uranium fuel cycle retains its attractiveness to many countries, further benefits can be gained by going to a range of SEU cycles, including those which exploit a unique synergism with LWR technology. All products of conventional reprocessing can be utilized without re-enhancement, or new technologies can be used that directly transfer spent LWR fuel in a CANDU reactor. Between these extremes a range of recycling options exists.

Existing CANDU reactors can be used to disposition ex-weapons plutonium freed up by disarmament treaties, or to create safeguarded stocks of U-233 in thorium fuel while significantly extending uranium resources.

The relative simplicity of construction and the fuel-cycle flexibility of CANDU technology makes it the best vehicle for introducing nuclear power to developing countries. CANDU technology gives countries with existing LWR technology the ability to greatly improve fuel utilization, while adding baseload supply.

The potential for customization to any country's needs, with competitive economics and within any level of domestic industrial infrastructure, gives CANDU technology strategic importance in the 21st century.

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